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# Global Ionospheric Processes

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**14. ABSTRACT**
The Global Ionospheric Processes basic research task has focused on three core areas: the equatorial ionosphere, the polar ionosphere, and active experiments. In equatorial ionospheric research, the group concluded work on previous solar maximum experiments including the Conjugate Points Experiment (COPEX), made preparatory investigations for C/NOFSA satellite mission, and carried out initial research with the satellite after launch. In the high latitudes, a chain of stations across the polar cap was completed with the installation of instruments at Station Nord, Greenland, to observe the formation and evolution of polar cap patches and scintillation-producing irregularities. Significant progress was made in understanding substorm plasma injections as they relate to subauroral plasma streams and other phenomena near the plasmasphere boundary. A number of advances were made in active experiments, especially with the HAARP facility. This included reproduction of artificial optical emissions from the E layer, quantitative determination of optical emission generation efficiency, and investigations into naturally occurring subauroral precipitation structures that could prove useful for controlled particle precipitation experiments. We also detail a number of technology transitions resulting from this research.

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## Illustrations (cont.)

## 1. INTRODUCTION

This report summarizes the scientific achievements and research activities of the Global Ionospheric Processes basic research task for the three-year period from October, 2006, through September, 2008. Metrics required by the sponsoring organization, the Air Force Office of Scientific Research (AFOSR), are available as an appendix to this narrative.

### 1.1 Task History and Overview

The Global Ionospheric Processes task has been an ongoing basic research project within the Ionospheric Hazards Specification and Forecast Section of the Air Force Research Laboratory Space Vehicles Directorate (AFRL/RVBXI). The task was managed by Dr. Edward Weber until his untimely death in 1998, after which Dr. Santimay Basu became the task leader. The present P.I., Dr. Todd Pedersen, became task leader in 2004 when Dr. Basu transitioned to part-time status. Due to a change in policy at AFOSR, the ongoing task was set to expire at the conclusion of FY08. A new 3-year task for FY09-11 has been proposed and accepted, and commenced in October 2008. This report focuses on the last three years of the original task falling within the tenure of the current P.I., with an emphasis on the final year, FY08.

The Global Ionospheric Processes Task has focused on ionospheric scintillation, the instability processes producing scintillation, and the large-scale structures associated with the unstable regions. Efforts have emphasized the high-latitude and equatorial ionosphere where scintillation is most common and has the largest impact on AF and DoD systems. As the name implies, the task operates or utilizes data from a large number of ionospheric measurement instruments and sites around the world. We have also carried out some studies of mid-latitude scintillation and traced these ionospheric phenomena through to actual system effects during major magnetic storm periods. Synergistic utilization of the HAARP facility built and operated by our section at AFRL has also been carried out under this task, producing a large number of groundbreaking results in the field of active ionospheric experiments.

### 1.2 Objectives

Although detailed objectives and research focus areas have evolved somewhat over the extended lifetime of the task, the core objectives have remained relatively constant and have ensured that our research efforts remain productive and relevant to the Air Force mission.

The specific objectives guiding our work the past several years are summarized as follows:

1) Define the global dynamics and multi-scale structuring of the ionosphere
2) Quantify the fundamental processes controlling ionospheric dynamics
3) Identify and isolate the drivers that destabilize the ionospheric plasma
4) Identify critical space weather parameters
5) Develop diagnostic sensors to provide measurements of critical parameters
6) Develop theoretical and numerical models of ionospheric plasma processes
7) Model outages in communication and navigation systems from space- and ground-based diagnostics of ionospheric plasma structures

## 2. SCIENTIFIC RESULTS AND PROGRESS

### 2.1 Equatorial Ionospheric Research

#### 2.1.1 Ground-Based and Satellite Studies in Preparation for C/NOFS

In the equatorial region, our efforts during the reporting period began in FY06 with incoherent scatter radar and optical measurements from Kwajalein Atoll in conjunction with overflights of the newly launched COSMIC satellites. This included making comparisons between our ground-based optical data and on-board optical measurements from the NRL TIP photometer during some excellent passes through equatorial plasma bubbles. This work contributed directly to the TIP photometer calibration and validation effort, and has since led to formal recommendations to USAF Space Command for future photometer instruments to be included in space weather missions.

This study, which focused on data acquired during a campaign at Kwajalein in September 2006, showed generally excellent agreement between the nadir-looking 135.6 nm photometer data and profiles extracted from mapped all-sky image data at 630.0 nm. It also made it very clear that non-imaging sensors in high inclination orbits are unable to discriminate between the large-scale latitudinal gradients in the equatorial ionization anomaly and smaller-scale longitudinal gradients at the edges of plumes (see Figure 1). Although this is a limitation for the high-inclination COSMIC constellation, simulated equatorial satellite passes generated from the ground-based imagery demonstrated that this same type of sensor would produce much more valuable information in a C/NOFS-type equatorial orbit, and may be ideal for a C/NOFS follow-on mission.

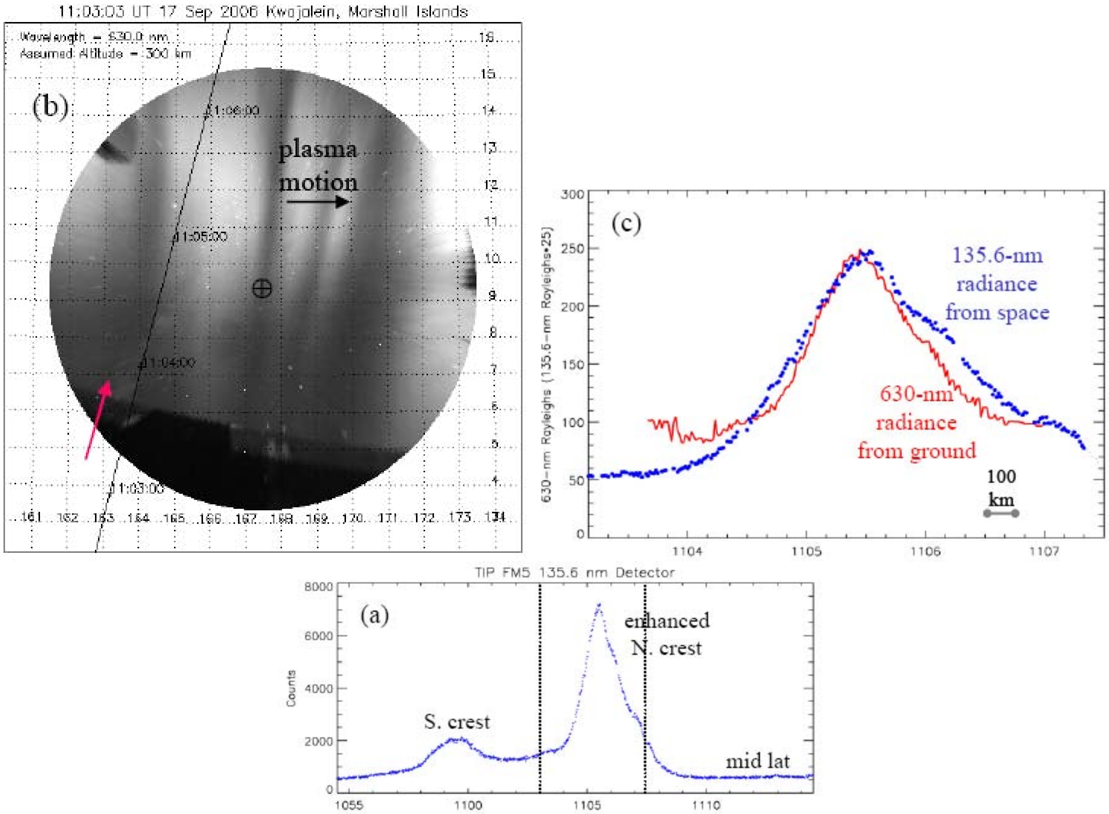


Figure 1. All-sky image of equatorial plumes over Kwajalein during a COSMIC satellite pass nearly parallel to the ionospheric plumes (left). Ground-based optical intensity observed along the orbit track matched well with down-looking measurements from the TIP photometer on board (right). The full satellite pass through the equatorial region (bottom) suggests a very asymmetric equatorial anomaly enhanced in the N. hemisphere, but the geometry of the pass as seen in the all-sky data instead indicates that the asymmetry most likely results from the gradient as the satellite crosses out of a plume and into the more dense region between plumes. See Coker et al. [2009].

Our equatorial effort also included comparisons of data from in-situ GPS radio occultation instruments and tri-band beacons on the 6-satellite COSMIC constellation to detect and characterize ionospheric scintillation and irregularities, using more easily interpreted measurements from ground sensors for comparison, especially the ALTAIR radar and AFRL ionospheric sensors at Kwajalein Atoll. This work was carried out in preparation for the launch of the C/NOFS satellite, which carries a similar radio beacon and GPS occultation instrument. The knowledge gained from this effort has proven directly applicable to C/NOFS after its launch in April, 2008, with the exception of parameters depending on the specific orbit geometry. The initial results of our Kwajalein studies suggested that apparent scintillation observed with the occultation instrument does not correlate well with ground-based measurements, and may not correspond to actual ionospheric effects much of the time. Efforts to localize scintillation on the

occulted links through back-propagation may eventually be able to resolve some of these ambiguities, however.

### 2.1.2 C/NOFS Launch and Campaign

After many years of delay, the Communications/Navigation Outage Forecast System (C/NOFS) satellite was finally launched into a near-equatorial (13° inclination) orbit in April 2008. In the final year covered by this report, our group began studies comparing data from the satellite with measurements from our various ground sites in the equatorial region, especially Kwajalein Atoll where the ALTAIR radar is able to make coherent and incoherent backscatter measurements of ionospheric plasma irregularities and plasma densities in conjunction with a suite of AFRL ground instruments.

A major campaign deploying scintillation, TEC, and some optical instruments to 4 different islands within Kwajalein Atoll and on neighboring Wotje Atoll was carried out in September 2008. Although the satellite went down during the core 2 weeks of this campaign we were able to successfully observe formation, development, and evolution of ionospheric plumes on several evenings and to track the C/NOFS satellite with both the radar and multiple tri-band beacon receivers. Although analysis of the campaign data had just begun at the end of the reporting period, initial indications were that conditions during the campaign were very near the threshold for instability development, with some nights never developing irregularities, others having bottomside ripples develop but never penetrate the F region, and yet others with fully developed plumes penetrating to the topside. In spite of equipment failures and logistical difficulties, we succeeded in acquiring optical images of plumes from both Kwajalein and Wotje, which will allow the altitude of the emitting layer to be derived rather than assumed and the position of the plumes to be unambiguously determined in 3 dimensions.

Strong gravity waves apparent in 557.7 nm emissions were also observed during one of the campaign days with the most dramatic plumes, and there were also at least 2 cases of plumes and/or bottomside ripples appearing before F-region sunset. We plan to analyze these and other precursor signatures that might have appeared in the radar, satellite, or ground-based data and compare these measurements with the C/NOFS forecast model under the new task beginning October 1, 2008.

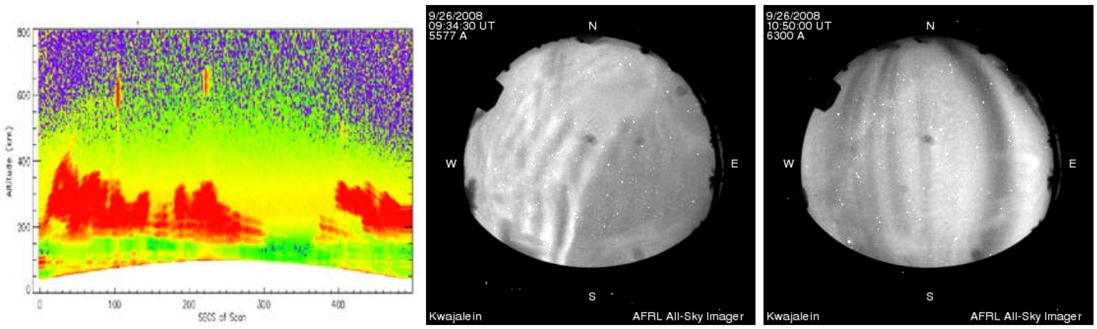


Figure 2. Coherent backscatter from developing ionospheric irregularities recorded by the ALTAIR radar (left), along with E-region gravity waves (center—557.7 nm) and F-region plumes (right—630.0 nm) seen in the all-sky imager during the September 2008 Kwajalein C/NOFS campaign.

### 2.1.3 COPEX Conjugate Points Experiment

Our group was a major participant in the Conjugate Points Experiment (COPEX) campaigns carried out in Brazil at the peak of the prior solar maximum in 2002. This experiment was designed to compare plasma densities, neutral winds, electric fields, and irregularity formation along a single flux tube sampled at the apex and both foot points. Ionosonde, optical, scintillation, and TEC data were collected in the S. magnetic hemisphere at Campo Grande and at the N. foot point of the field line in Boa Vista, while coherent backscatter radar, TEC, and scintillation measurements were also made at the midpoint on the magnetic equator in Alta Floresta. Analysis of this rich data set in collaboration with our Brazilian colleagues had been ongoing since the experiment, but results first reached the publication stage during the reporting period.

Comparison of optical data from the two conjugate points has convincingly demonstrated the direct mapping of large-scale features along the magnetic field, with optically-derived drift velocities agreeing well also. The drift velocities showed some difference between the two hemispheres, but it is not clear at this point whether or not this difference is fully consistent with mapping of electric fields along field lines, which have significant orientation and intensity gradients resulting from the sharp curvature of the magnetic equator in the S. American sector. This effort as published in Abdu et al. [2009] investigated large scale bottom side wave structure seen at conjugate sites as a precursor to ESF, quantified the effect of the evening pre-reversal electric field/vertical drift (PRE) on vertical bubble growth as indicated by the time delay in ESF onset at off-equatorial sites, and discussed the competing influences of the evening vertical plasma drift and trans-equatorial wind in favoring or suppressing the development of equatorial ionospheric irregularities. Work published by Sobral et al. [2009] compared optical images from the two conjugate hemispheres and modeled the neutral wind effects but found little or no difference in motion between the two hemispheres. Optical images clearly showed the direct conjugacy of large-scale ionospheric structures.

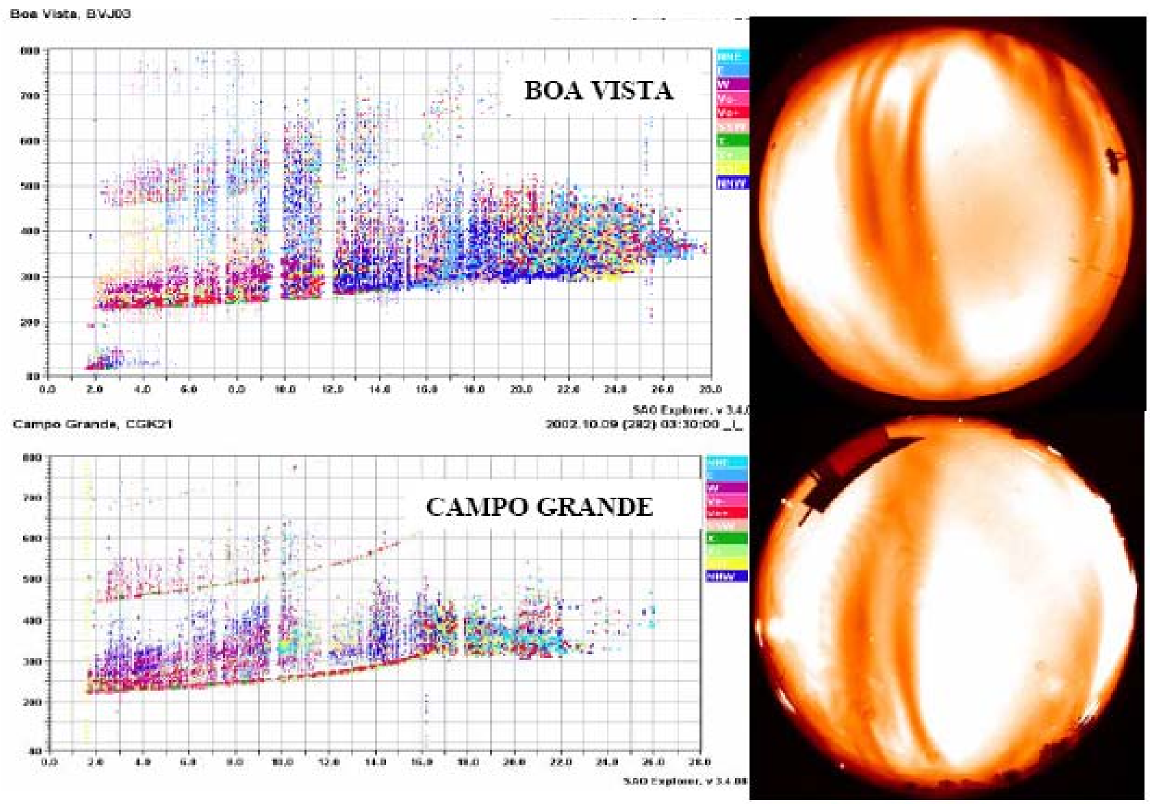


Figure 3. Ionograms and optical images from conjugate hemispheres during the COPEX experiment. From Abdu et al. [2009].

### 2.1.4 Other Equatorial Ionospheric Research

In Beach and Baragona [2007], members of our task published a study of quasi-periodic scintillation in the equatorial ionosphere intended to determine the minimum scale size of horizontal gradients. However, this work instead revealed the near-ubiquitous but previously unrecognized presence of cross-satellite interference in GPS signals. Now that this effect is understood, it can be screened out of GPS data analyses seeking ionospheric structure. Members of our task also completed a study comparing plasma velocities along the S. American magnetic meridian, which found a large gradient between the southern anomaly and northern anomaly, and a significant increase in drift velocity over the equator compared to the anomaly peaks. We also developed a technique to identify bottom-side sinusoidal irregularities over the equator, which have previously been difficult to separate from plasma bubbles, resulting in a scintillation climatology that is a mixture of the two effects.

In June 2007, we installed ionospheric measurement instruments in Cape Verde, the first of a number of planned stations spanning the African longitude sector. In 2007 we also completed a study of daily variability in the equatorial anomaly plasma density which found the ionospheric weather dominated by 2-5 day periods creating differences

of two to seven in density, along with a preferred 3-day periodicity which may allow empirical 72 hour forecasts to be produced and utilized even though the cause of this effect remains obscure.

Additional results included a study of the longitude dependence of equatorial irregularities, using multiple space- and ground-based instruments, which found that even under quiet conditions local irregularity generation is extremely variable. This variability is attributed to different zonal neutral winds. A study of storm effects on equatorial irregularity generation was also completed and published this fiscal year. The primary finding in this work was that only longitude sectors that are near the dusk terminator at the time of onset are directly affected. This is a key basic research result necessary for effective forecasting of space weather and its effects on systems.

#### 2.1.5 Summary of Equatorial Research

Our efforts in the equatorial region during the reporting period consisted primarily of investigations in preparation for the C/NOFS satellite mission, in addition to ongoing research utilizing earlier data sets. Key findings included the difficulty of localizing scintillation on GPS occultation links, recommendations for future space-based photometer instruments on equatorial orbiting satellites, and detailed investigations of conjugate effects in the Brazilian sector. The C/NOFS satellite finally was successfully launched in the latter half of the final year of the reporting period. One campaign was conducted at the very end of the period in September 2008, but the satellite was not operating properly at the time and analysis of the ground-based data had only just begun at the conclusion of the reporting period.

### 2.2 Polar Ionospheric Research

Our focus in the high-latitude region is on understanding the source, creation mechanisms, evolution, structuring, and irregularity development in polar cap patches, the large (>100 km) clouds of enhanced plasma density which are responsible for the bulk of ionospheric scintillation and other RF effects in the polar region. Although ionospheric densities and associated system impacts have been very low as the reporting period coincided with the lowest solar minimum in recent history, we have worked on and completed analysis of several data sets collected during the most recent solar maximum, especially the storm periods during October and November 2003. The reporting period also saw establishment of a fully instrumented joint US/Danish ionospheric monitoring station at Station Nord in Northeast Greenland.

We have done some other work on subauroral plasma stream dynamics related to substorm effects as well as highly structured subauroral precipitation, which is also a post-substorm phenomenon affecting subauroral to middle latitudes.

### 2.2.1 Station Nord Project

In the first year of the reporting period, our group successfully established a key new research site in July and August 2006 at Station Nord, a Danish military outpost in northeast Greenland. This was carried out under an international cooperative agreement with the Danish Ministry of Defence and the Danish Meteorological Institute. The initial setup required several weeks of hard physical labor under harsh weather conditions following several years of planning and negotiations to secure funding for the instruments and establish the international agreement. The greatest difficulty was encountered in construction of the ~100’ tall ~400’ wide ionosonde transmit antenna, as the deep snow and frozen ground remaining late into the season prevented excavation for installation of the guy anchors and receive antennas. After extensive attempts to dig through the ice and permafrost with hand tools and heavy equipment, the anchors were finally secured by placing them in 55 gallon drums, filling the drums with dirt, and then placing a truck load of additional dirt on top of each drum.

Instrumentation originally installed at the site in FY06 included a digital ionosonde, all-sky imager, GPS TEC receiver, tri-band beacon receiver, and 250 MHz scintillation receiver, all of which were funded by the USAF International Cooperative Research and Development (ICR&D) program as a matching contribution to the high latitude ionosphere research carried out under the Global Ionospheric Processes task. Station Nord is in a unique location, situated almost exactly midway between the incoherent scatter radar and other diagnostics in Svalbard, Norway, and the USAF Upgraded Early Warning Radar site in Thule, Greenland, which allows polar cap patches to be observed and monitored from their creation through to their actual impacts on operational systems. The capabilities provided by this location are expected to resolve many of the ambiguities remaining in radar observations of patch formation over Svalbard, particularly that of longitudinal plasma transport into the plane of the radar scans along the magnetic meridian. Establishment of this new site, and the struggles to install the instruments under harsh conditions, was reported in a number of DoD press releases, including the DoD, USAF, and AFMC web sites.

Figure 4. (Left) Ionosonde transmit antenna guy wire anchor locations surveyed in a snow field surrounding a 100’ antenna pole at Station Nord in late July 2006. (Right) Global Ionospheric Processes task members laying out the ionosonde antenna radiating elements in the snow and meltwater in August 2006.

The Station Nord site reached full operation in FY07 and began reporting summary data in real time after repair and maintenance performed during the summer of 2007. The first full year of data was retrieved during the annual maintenance visit in summer 2008 and data analysis is well under way as of the time of writing. We expect the data will show the early stages of patch formation and evolution as they leave the cusp over Svalbard, as well as the onset of irregularities, although direct observations of patch formation on the noon side of the polar cap will likely have to wait until solar activity picks up at the beginning of the new solar cycle. We hope to tie the observed large-scale structure of the patches to specific creation mechanisms and model their structure and evolution well enough to allow use of the reconstructions in HF raytracing for geolocation, OTH radar, and communication purposes.

Fields of View at 250 km Altitude

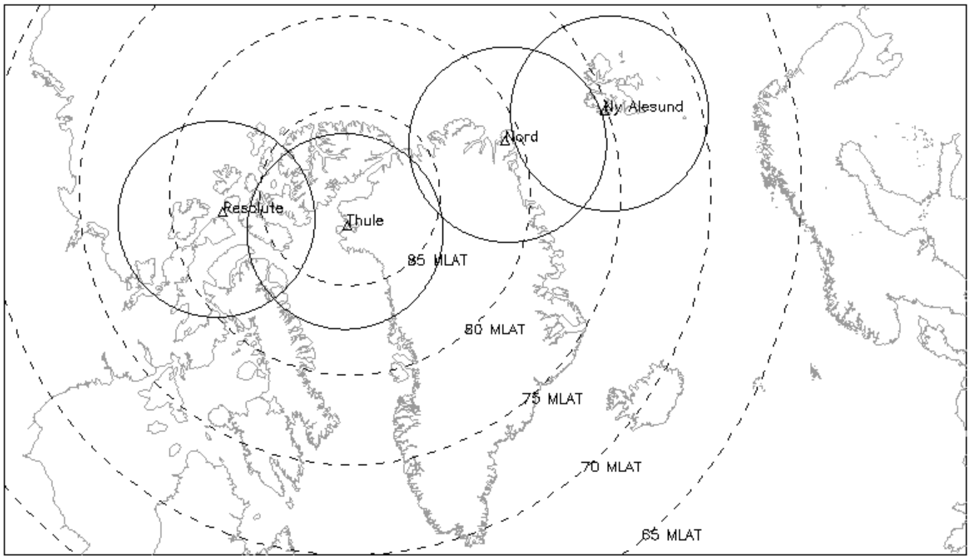


Figure 5. Fields of view of instruments along the completed chain of high-latitude stations from Svalbard (far right) to Nord (2nd from right) to Thule/Qaanaaq (2nd from left) and the new NSF radar site under construction in Resolute Bay, Canada (left).

### 2.2.2 Structured Subauroral Precipitation

Another high-latitude result produced during the period of coverage was identification of highly structured hard subauroral precipitation associated with the outer edges of the radiation belts and ring current, which we found to be commonly present far equatorward of the traditional aurora during quiet periods.

This entirely natural phenomenon was first noticed at HAARP in 2004 when a more modern all-sky camera owned by the task was brought to the site for artificial optical emission experiments. Numerous cases were observed in 2004 in conjunction with F-region airglow experiments, which in some cases were disrupted by the sudden onset of the precipitation. After discussion with colleagues and presentation of the data at conferences, it was found that this type of precipitation had been observed a few years earlier by Kubota et al. [2003] using a bare-CCD imager from Poker Flat. They termed the phenomena “co-rotating aurora” because it typically appeared during quiet times and had relatively little motion compared to typical aurora which tends to flicker and move rapidly. Our study based on data from HAARP [Pedersen et al., 2007] confirmed the Kubota et al. [2003] findings and added significant new information, including co-location of the precipitation regions with areas of MeV particle “contamination” on DMSP detectors, identification of small-scale (~10-30 km) swirling vortex-like structures dubbed “angels” as a common end state of an instability process, and location of the precipitation equatorward of sub-auroral plasma streams (SAPS). This latter fact created

a terminology difficulty leading us to refer to the phenomenon as “hard subauroral particle precipitation” rather than “aurora” located equatorward of the already well-known “sub-auroral” plasma streams.

The hard subauroral precipitation is of significant interest to USAF operations because it represents a natural mechanism dumping energetic trapped particles out of the same flux tubes occupied by relativistic radiation belt particles. One possibility is that cold plasma from the plasmasphere alters the pitch angles of energetic particles on the same field lines, causing them to precipitate out. The structured pattern seen in the precipitation, and presumably the instability causing it, would then mimic structure in the outer plasmasphere. The range of pitch angles available in these structured regions, from fully trapped to precipitating, also provides fertile ground for active experiments attempting to artificially induce particle precipitation, whether through ground-based VLF transmissions, space-based VLF wave generation, or chemical releases. Additionally, the bulk motion of the small-scale vortex-like structures seen in the precipitation is likely to provide a means of measuring penetration electric fields in the near subauroral region, an important driver for day-to-day space weather variability in the mid-latitude and equatorial ionosphere.

Our studies additionally determined that the hard precipitation was responsible for highly structured D-region absorption affecting HF propagation and heating. Examples of F-region heating being blocked in areas of hard precipitation while occurring unhindered in the gaps between them was presented in another paper published in Annales Geophysicae [Pedersen et al., 2008a].

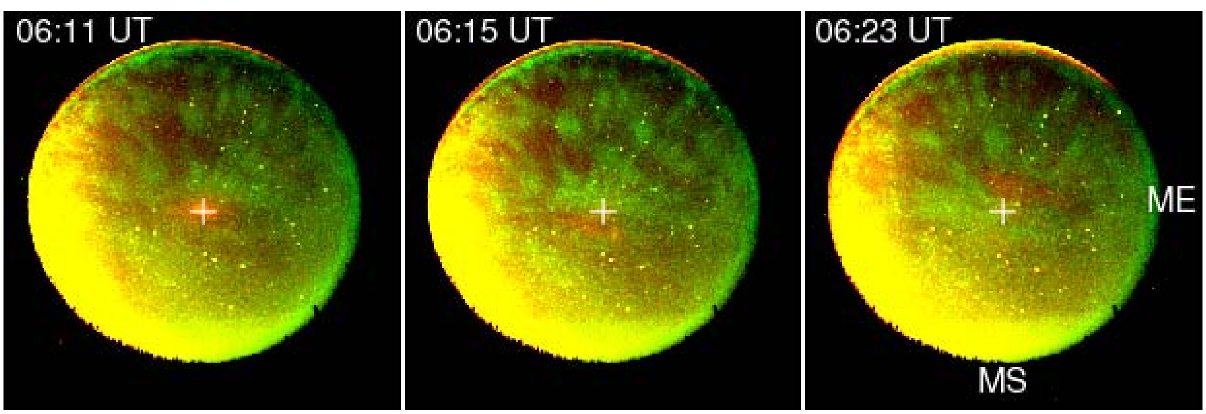


Figure 6. Artificial optical emissions (red) appearing only in gaps in the natural precipitation (green) which creates absorption of the HF transmitter beam. From Pedersen et al. [2008a].

## 2.3 Other High-Latitude Research

In addition to efforts to establish a new observation site at Station Nord, we have also pursued polar cap patch studies utilizing past data sets and campaign data from other high-latitude sites.

We carried out a patch observation experiment utilizing the EISCAT Tromso and Svalbard radars in December 2006 in cooperation with our Norwegian colleagues, but the radar run was impacted by a large magnetic storm event resulting in extremely low plasma densities ($N_{mF2} < 10^4$/cc) and accordingly poor radar signal-to-noise levels. We were, however, able to make some auroral measurements during this event, including high-time-resolution observations with our EM-CCD camera.

We also spent significant effort pursuing a longer-term study of N-S aligned arcs observed connecting directly to the cusp, which are associated with strong precipitation and huge ion drifts, and appear to result from transient bursts of reconnection. Several new papers on patch occurrence as observed in the Norwegian sector were produced and published in FY07 by our colleagues at the University of Oslo under an EOARD grant sponsored by our task, which also provides logistical support for our research and monitoring instruments in Norway and Svalbard [Lorentzen et al., 2007; Moen et al., 2007; Moen et al., 2006]. Through this collaboration we also produced significant new results on the formation of polar cap patches, especially new observations of patch formation and physical constraints on motion relative to various boundaries that are not currently included in models [c.f., Lockwood et al., 2005a,b].

We also analyzed several cases of polar cap patches at Qaanaaq, Greenland during major magnetic storms in the fall of 2003. Although some of these are larger, more intense, and unusually shaped versions of traditional density-based patches, other features in the same data sets appear to be a previously unknown type of highly structured particle precipitation which moves rapidly antisunward with the prevailing convection rather than forming sunaligned or transpolar arcs. If this new phenomenon proves to be common during storm periods, and has associated plasma density signatures (increases in $N_{mF2}$ or TEC), it may force a significant re-evaluation of past patch occurrence statistics which are the primary supporting evidence behind various theories of patch formation.

One of the studies based on past data from Qaanaaq is an analysis of polar cap patches occurring on November 20, 2003 during a storm period [Valladares et al., 2008]. These patches were much more dense and bright than typical patches, and had generally fuzzy shapes which changed rapidly at times. We analyzed optical images from Qaanaaq, Greenland, in the central polar cap to determine the location, extent, and motion of the patches, and then used global convection velocities from the SuperDARN network to drive a physics-based model accounting for recombination and other processes. By running the model in reverse, we were able to match the observed patches with incoherent scatter radar measurements from Sondrestrom and determine the origin of the patches to be in the afternoon sector, contrary to the findings of other recent studies

suggesting that patch plasma originates from precipitation in the morning sector [MacDougall and Jayachandran, 2007; Bust and Crowley, 2007].

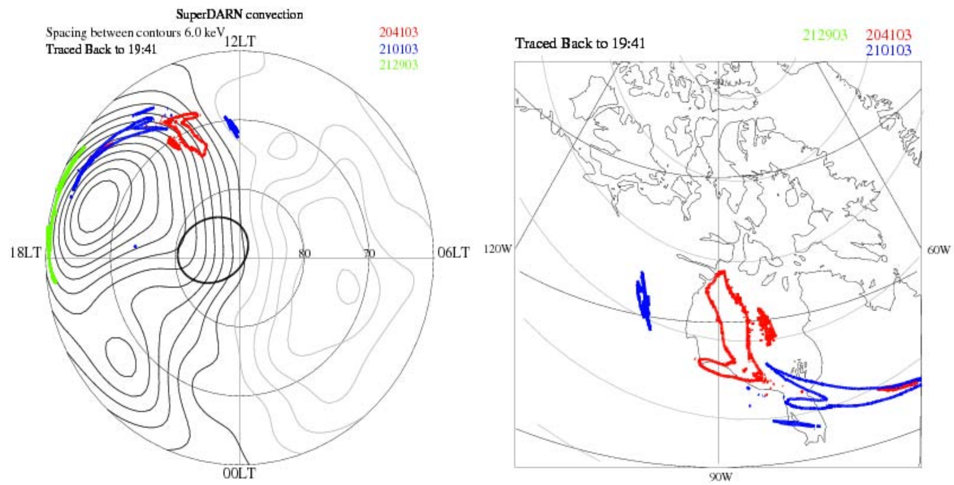


Figure 7. Locations of polar cap patches (red and blue) traced back to the source region over Hudson Bay from observations within the imager field of view at Qaanaaq (black circle), shown in magnetic coordinates (left) and geographic coordinates (right). From Valladares et al. [2008].

Another study from the active period during the autumn of 2003 was the October 30-31 "Halloween" storm. We used GPS TEC measurements from throughout the polar region to drive a tomography algorithm and compared the results with optical measurements from Qaanaaq in the central polar cap. A comparison of TEC measurements from an individual receiver in Thule and optical intensities from Qaanaaq showed the large-scale features to correspond qualitatively between the two data types, but the amplitudes of the density fluctuations were not linear, and the high degree of structure seen in the optical emissions was not fully captured in the TEC tomographic reconstructions. This work has now been published by Yin et al. [2008].

### 2.4 Summary of High-Latitude Research Activity

We have maintained a high level of research activity at high latitudes during the reporting period, between analysis of data from the previous solar maximum and establishment of a chain of stations linked by the new observation site at Station Nord in Northeast Greenland. We anticipate that this new chain will provide data leading to resolution of many outstanding research questions during the upcoming solar maximum.

## 2.5 Active Ionospheric Experiments

The period covered by this report included completion of the full 3.6 MW transmitter array at the HAARP facility. Our work therefore includes relatively mature studies of phenomena produced repeatedly at the previous 960 kW partial power level as well as initial results from the first experiments at full power. We also participated in several heating experiments at other facilities, such as the HIPAS heater near Fairbanks, Alaska, and the EISCAT heating facility in Tromso, Norway, during the period, as well as some chemical release experiments.

### 2.5.1 HAARP Research at 960 kW

Our group has conducted research campaigns at the HAARP facility annually or more frequently since initial operation of the facility in 1999. Several campaigns occurred during the reporting period, although a planned joint HAARP-HIPAS campaign in 2007 was limited to operation of the HIPAS facility as testing related to completion of the HAARP array prevented operation of HAARP. We also analyzed data from several previous campaigns in 2004 and 2005. Our work in this period was greatly enhanced by participation in the task of Dr. Michael Kosch of Lancaster University, who spent a total of 1 year with our group as a National Research Council Senior Associate.

By careful measurement of the intensity of optical emissions at different points in the dispersion curves, we have been able to isolate up to three simultaneous processes responsible for conversion of HF power into ionospheric effects. These include parametric decay and thermal parametric instabilities. We have also identified effects from Z-mode propagation escaping into the topside ionosphere, which may open a new range of altitudes over which effects could be produced. We were also able to stimulate natural ULF resonances near 0.75 Hz through HF heating.

High temporal resolution experiments (~2 sec) at HAARP made in 2005 showed the initial onset of heating to occur in very localized filaments a few km across, and eventually to diffuse from these hot spots to the surrounding regions. An intriguing result was that the hot spots only appeared in the second short pulse from the transmitter, suggesting that the first short pulse was required to generate the structures [Pedersen et al., 2008a.] The high temporal resolution observations were inspired by the results of our analysis of experiments from the previous winter (2004), which captured for the first time the actual process of focusing in the magnetic zenith.

Initial green line emissions were spread relatively uniformly across the beam but within 1 minute had collapsed into the familiar magnetic zenith spot, with intensities outside the spot actually decreasing. Ray tracing suggests that this focusing most likely occurs upon reflection from the ionosphere, where the contour of reflection altitude is distorted into a convex shape by thermal increases in the reflection altitude in response to

the heating.  Refractive effects on focusing were found to be insignificant.  These results suggested that HF waves can be focused much more effectively, and with much less perturbation of the ionosphere required, through reflection rather than refraction [Kosch et al., 2007.]

Analysis of altitude profiles of artificially induced 630 nm emissions, acquired from a remote side-looking imager system, allowed us to extract altitude-resolved emission lifetimes for the first time [Pedersen et al., 2008a.]  This key result, spanning more than 150 km in altitude, may allow neutral density profiles to be determined for production and calibration of atmospheric drag models required for improved Space Situational Awareness.  These results are discussed in more detail in the Technology Transitions section of this report.

The model fitting technique developed to determine emission lifetimes also proved extremely valuable in determining the magnetic aspect angle dependence of interactions in quantitative terms for the first time.  The dominant feature of F-region ionospheric heating at HAARP during the ~8 years the facility operated at 960 kW total power was the magnetic zenith effect, where optical emissions and other heating effects maximize when the transmitter beam is directed parallel to the magnetic field.  A shift in location of the optical emissions was first noticed by Kosch et al. [2000] from data taken at EISCAT during 1999, the first year confirmed optical emissions were observed at both EISCAT and HAARP.  Pedersen and Carlson [2001], working under this task, reported the first observations from HAARP and found a knob of brighter emissions in the magnetic zenith that could not be explained by plasma transport or drift of excited O ($^1$D) atoms.  Full exploration of this phenomenon by actively directing the transmitter into the magnetic zenith was accomplished at HAARP in the February 2002 campaign.  Optical observations from this campaign were published by Pedersen et al. [2003], while similar experiments at EISCAT using the incoherent scatter radar as a diagnostic were reported by Rietveld et al. [2003].  Since 2002, magnetic zenith pointing has become the default for F-region heating at HAARP, leaving the dependence of heating on magnetic zenith angle still unquantified.  In February 2005, a beam swinging experiment was run under relatively stable ionospheric conditions to quantitatively determine the dependence of optical emissions on angle relative to the magnetic field.  Due to the long lifetime of the excited O ($^1$D) atoms and the frequent repositioning of the transmitter beam, significant modeling and analysis of the temporal structure of the airglow emissions, as well as extensive modeling of the background ionospheric conditions, was required.

We completed the analysis of this experiment in 2008 and submitted a paper on the subject, which has now been published by the Journal of Geophysical Research [Pedersen et al., 2008b].  The fundamental findings of this study are that there are two components to the optical emission distribution; just over half represented by a Gaussian of ~7° width centered on the magnetic field line position, and a larger N-S elongated distribution ~15°-17° in half width centered on a point about 1/3 of the way between magnetic zenith and

vertical. All emissions are significantly suppressed beyond ~15°-20°. Ray tracing through a high-fidelity 4-D ionospheric reconstruction indicated that transmitter power was able to reach the upper hybrid altitude over a much wider range than the observed emissions, suggesting that the orientation of the rays while passing through the upper hybrid layer is important for exciting optical emissions and presumably other heating effects. This work represents a baseline for the spatial distribution of emission intensity at frequencies near the 2$^{nd}$ gyroharmonic at the 960kWpower level applicable for the period from 1999-2007 at HAARP and for most other ionospheric heating facilities.

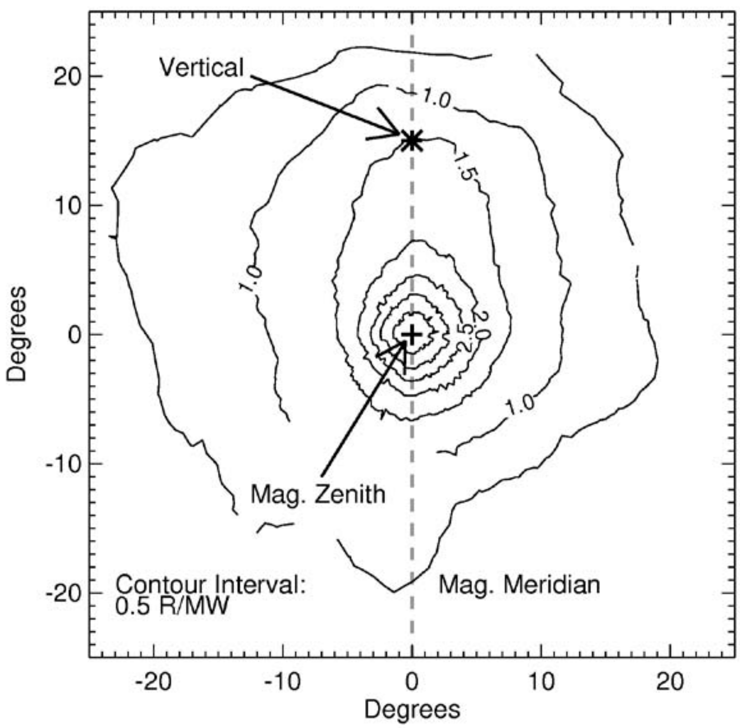


Figure 8. Contours of HF emission production efficiency at the 960 kW power level as a function of angle relative to the magnetic field. From Pedersen et al. [2008b].

Although F-region artificial optical emissions are commonplace at HAARP and other heating facilities, emissions are also possible from the E region when densities there are high enough to interact with the transmitter waves. This effect was first observed by Djuth et al. [1999] at Arecibo in a thin sporadic E layer, and resulted in extraordinarily bright (~80 R) emissions at 557.7 nm and an absence of 630.0 nm emissions.

A heating experiment targeting an auroral E layer at HAARP in March 2004 produced numerous km-scale artificial "speckles" of more than 1 kR in brightness at 557.7 nm above the auroral background of several kR, which were bright enough to potentially be visible to the naked eye. The speckles turned on and off in synch with the 7.5s pulsing of the transmitter, which was operated at 5.95 MHz in an E layer with a critical frequency close to the transmitter frequency. This unexpected and unprecedented result was published in Nature [Pedersen and Gerken, 2005] and generated interest in the

popular press. Attempts to reproduce this astonishing result have been made nearly every time an E layer appeared during subsequent campaigns, but were unsuccessful until a new case was identified in November 2007 while examining data from a March 2006 experiment. This has now been written up and submitted for publication in the Journal of Geophysical Research [Pedersen et al., 2009]. This new case was not as dramatic, with a smaller number of speckles at intensities of only 40-50 R above the slowly moving precipitation-produced background, but was at the same 5.95 MHz frequency and power level as the original observations. The most remarkable feature of the new observations is the persistence of the speckles over multiple minutes instead of only across the much shorter (5 sec) on-off cycles. The speckles also showed no preference for the beam center, in spite of a large range of E-layer densities available there along a sharp gradient in the natural precipitation. The persistence and sparse distribution of the features has suggested that either a longer-lived metallic plasma derived from meteoric particles is responsible, or that perhaps the active resonance is on the top side of the E layer and only available in holes in the layer or along the edges of density enhancements. These hypotheses will be actively tested in future campaigns by scheduling experiments during periods of enhanced meteor fluxes and by observing sodium emissions from the E-layer during the experiments to determine the extent of meteor trails or other natural metallic plasma present.

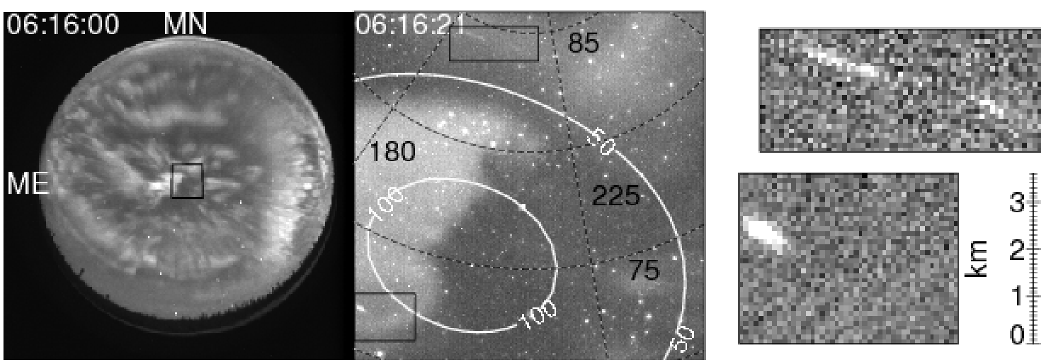


Figure 9. All-sky image (left) of large-scale precipitation structure producing enhanced densities in the E region ionosphere. Images from a narrow-field camera (center) show several artificial 557.7 nm optical enhancements created by the HAARP transmitter beam (power contours shown in white) which are less than 1 km in size (right). From Pedersen et al. [2009a].

Prior to the upgrade of the HAARP facility we also made a direct comparison between optical emissions from the HAARP transmitter and the HIPAS facility near Fairbanks. The results showed no significant difference in optical intensity between the two facilities, in spite of the much higher nominal ERP of HIPAS at low frequencies, suggesting that F-region optical emissions may already be near or beyond saturation. Since the measurements, however, we learned that the standard beam model used by

researchers to determine the power density at HAARP was low by a factor of 3, and therefore the power densities relevant to the comparison were actually comparable.

### 2.5.2 HAARP Experiments at Full 3.6 MW Power Level

The HAARP transmitter was completed in the summer of 2007 and the first science campaign at the full power level of 3600 kW was conducted the following winter in February 2008. Observations were carried out by our group using local and remote optical instruments as well as scintillation receivers operated from vehicles to observe the intersection of the satellite signal with the heated region over HAARP. One of the most interesting results is that the heater effects are no longer as dependent upon the magnetic field but show similar effects both in the vertical and magnetic zenith. The typical appearance of the optical emissions in the new power regime are a uniform disk in the center of the beam with a very sharp edge at about 50% maximum power surrounded by a dark area and a ring of enhanced emissions forming tall rays at about the 10% power level [Pedersen et al., 2009b]. We also collaborated with researchers from Norway, Sweden, and Britain to diagnose experiments to examine self-focusing at high temporal resolution, irregularity generation and suppression by O- and X-mode transmissions, and a unique beam configuration utilizing orbital angular momentum to produce ring-like power distributions. This last experiment has been written up and now published [Leyser et al., 2009].

### 2.5.3 Other Active Experiments

In October 2005 we participated in a campaign at the EISCAT radar facility in Tromso, Norway, and made critical optical measurements in conjunction with the incoherent scatter radar that have established for the first time an empirical basis for use of 428 nm emissions from ionized molecular nitrogen in large-scale optical mapping of ionospheric conductance. We also searched for sodium emissions from heating of the ionospheric E-region, although this part of the experiment produced only negative results. We also collaborated with European colleagues to provide optical observations during experiments the European SPEAR heating facility using our research imager in Svalbard.

Experiments we participated in using the HIPAS facility near Fairbanks, Alaska, have resulted in detection of previously unreported optical emission lines from ionized species [Mutiso et al., 2008], the first incoherent scatter radar measurements of interactions at the 2$^{nd}$ gyroharmonic, obtained with the new Poker Flat incoherent scatter radar [Kosch et al., 2009], and 3-D tomographic reconstruction of the optical emission distribution from AFRL cameras at HAARP and HIPAS [Gustavsson et al., 2008].

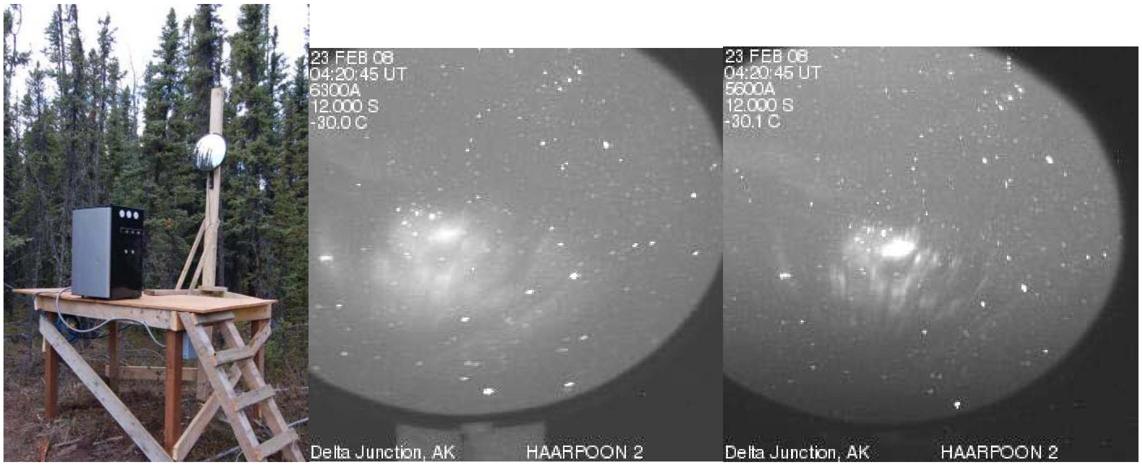


Figure 10. Low-cost wide-angle imager deployed at Delta Junction, Alaska, to make remote observations of optical emissions generated by the HAARP facility 250 km away (left). Designed by members of the task, the imager uses a converted dorm room refrigerator to provide a controlled environment for two high-sensitivity CCD cameras, while the mirror mounted on the post broadens the field of view without requiring expensive telecentric optics. High-quality data acquired by the system during the first HAARP experiments made at full power are shown in the center and right panels, and reveal a spot surrounded by a ring of filaments extended in altitude.

We also participated in a new type of active ionospheric experiment in February 2008 by making radar and optical measurements of the effects of the Space Shuttle OMS engines on the ionosphere, which has direct relevance to USAF Space Situational Awareness efforts.

## 3. TECHNOLOGY TRANSITIONS

The ultimate goal of all basic research conducted by our task is to assist development of new technologies of relevance to the US Air Force and Department of Defense. In this section we provide details on a few selected examples of applied research transitioned from our basic research during the reporting period.

In Section 2.3 we mentioned that we were able to determine the time constants for the decay of 630.0 nm $O(^1D)$ atomic oxygen emissions by fitting optical data to a simple exponential model. This has direct implications for USAF operations as a potential means of remotely measuring neutral atmospheric densities, especially at altitudes too low for direct in situ sampling.

Because the intrinsic lifetime of the state producing the 630.0 nm emission is approximately 2 minutes, deactivation of the excited state through collisions with atmospheric neutral species is typically significant at all altitudes below the topside of the F region, resulting in effective lifetimes for the emission that are significantly shorter than the intrinsic lifetime. The effective lifetime as observed in the decay of transmitter-produced emissions is therefore a means of measuring the ambient neutral density as a

function of altitude. Previous studies including Gustavsson et al. [2001] had determined the effective lifetime as the interaction region rose and fell with time, but measurements were limited to a small range of altitudes near the peak of the optical emissions. With high-quality side-looking data, we have been able to determine the effective lifetime simultaneously over an extended altitude range of more than 150 km for the first time [Pedersen et al., 2008a]. We have entered a collaboration with SRI International to analyze these effective lifetime measurements and derive neutral densities for comparison with models and other measurement techniques (see figure below). A paper on this work has been submitted and is now published [Kalogerakis et al., 2009].

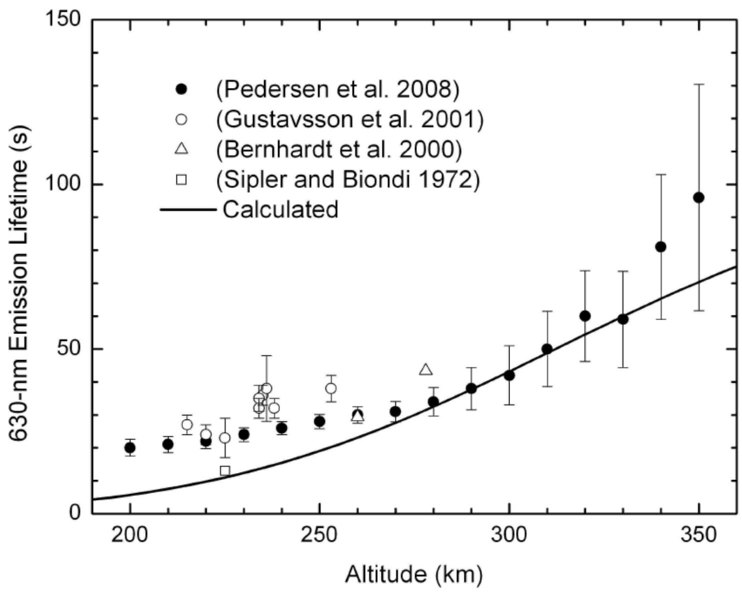


Figure 11. Published 630.0 nm emission lifetime measurements compared with calculated values from an atmospheric model. From Kalogerakis et al. [2009].

Another promising recent follow-on use has been utilization of our narrow-band optical imaging capability, normally used to determine plasma densities in the ionosphere, to diagnose the presence and distribution of reactive oxygen species (primarily OI) in plasmas produced by electrical discharges. In collaboration with Prof. Spencer Kuo of Polytechnic University, we have imaged several different plasma torches designed for decontamination of biological warfare agents in mail and on everyday surfaces, enhanced coagulation of blood and sterilization of wounds, and igniters for scramjet engines. One of the critical factors for practical application of torch-generated plasmas is the distance from the nozzle at which effluent species remain in excited states. This is difficult to determine in general, but can be readily measured by narrow-band optical imaging of the emission lines produced by the excited states. In the case of reactive oxygen species, the target wavelengths are identical to those produced in the ionosphere and upper atmosphere. Our imaging and calibration capabilities and dark room facility have allowed various configurations, especially placement and orientation

of plume-guiding magnets, to be tested with real-time feedback. Two of these efforts were written up and published or submitted in the final year of the period [see Kuo et al., 2008; Chen et al., 2009].

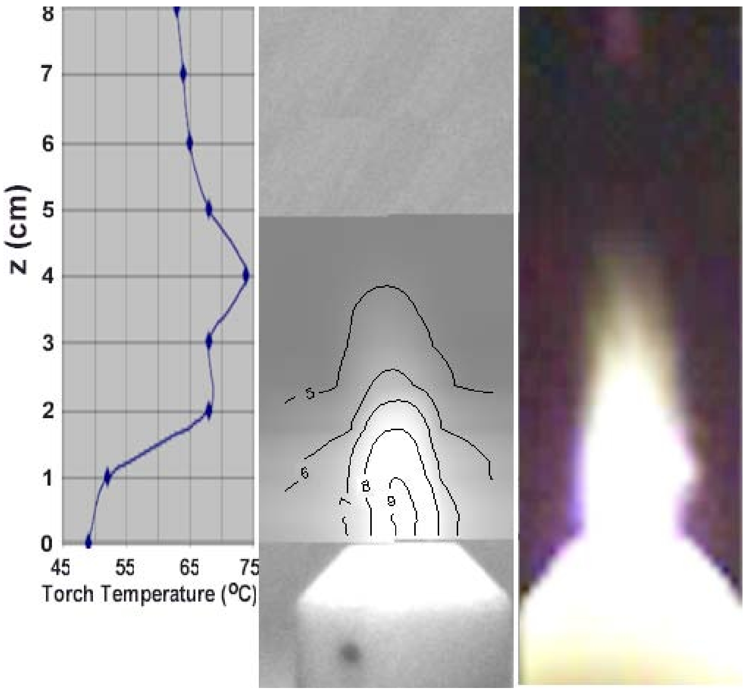


Figure 12. Plasma torch nozzle and plume seen in white light with a video camera (right), high-dynamic-range composite measurement of the density of excited oxygen from AFRL 777.4 nm observations (center), and a temperature profile through the plume (left). After Kuo et al. [2008].

## 4. SUMMARY AND CONCLUSIONS

The Global Ionospheric Processes basic research task has produced a wide range of significant basic science and technology transition results over its history. The final three years, from FY06-08 have been summarized in this report. Research efforts have focused on ionospheric scintillation and related large-scale structures, instability processes, and propagation effects. Efforts have been organized into polar, equatorial, and active experiments categories. We have made significant progress in all these areas, and expect valuable new results under the new task, especially with the C/NOFS satellite on orbit, our research site in NE Greenland in full operation, and the HAARP facility operating at full power. A proposal for a new 3-year task has been submitted and accepted, with the new effort expected to start in October 2008.

## REFERENCES

*References cited in the body of this narrative are included in this section. Please see the separate appendix for a complete listing of publications produced by the Global Ionospheric Processes task during the final year of the reporting period.*


Abdu, M. A., I. S. Batista, B. W. Reinisch, J. R. de Souza, J. H. A. Sobral, T. R. Pedersen, A. F. Medeiros, N. J. Schuch, E. R. de Paula, and K. M. Groves, Conjugate Point Equatorial Experiment (COPEX) campaign in Brazil: Electrodynamics highlights on spread *F* development conditions and day-to-day variability, *J. Geophys. Res.*, **114**, A04308, doi:10.1029/2008JA013749, 2009.

Beach, T. L., and C. A. Baragona, Quasiperiodic scintillation and data interpretation: Nongeophysical GPS amplitude fluctuations due to intersatellite interference, *Radio Sci.*, **42**, RS3010, doi:10.1029/2006RS003532, 2007.

Bust, G. S., and G. Crowley (2007), Tracking of polar cap ionospheric patches using data assimilation, *J. Geophys. Res.*, **112**, A05307, doi:10.1029/2005JA011597.

Chen, Cheng-Yen; Hsin-Wen Fan; Kuo, S.P.; Jenghwa Chang; Pedersen, T.; Mills, T.J.; Cheng-Chiu Huang; Blood Clotting by Low-Temperature Air Plasma, *IEEE Transactions on Plasma Science*, **37**, Issue 6, Page(s):993 – 999, 2009.

Coker, C., K. F. Dymond, S. A. Budzien, D. H. Chua, J. Y. Liu, D. N. Anderson, S. Basu, and T. R. Pedersen, Observations of the ionosphere using the Tiny Ionospheric Photometer. *Terr. Atmos. Ocean. Sci.*, **20**, 227-235, doi:10.3319/TAO.2008.01.18.02(F3C), 2009.

Djuth, F. T., et al., Large airglow enhancements produced via wave-plasma interactions in sporadic *E, Geophys. Res. Lett.*, **26**(11), 1557–1560, 1999.

Gustavsson, B., et al., First Tomographic estimate of volume distribution of HF-pump enhanced airglow emission, *J. Geophys. Res.*, **106**(A12), 29,105–29,123, 2001.

Gustavsson, B., Kosch, M., Wong, A., Pedersen, T., Heinselman, C., Mutiso, C., Bristow, B., Hughes, J., and Wang, W.: First estimates of volume distribution of HF-pump enhanced emissions at 6300 and 5577 Å: a comparison between observations and theory, *Ann. Geophys.*, **26**, 3999-4012, 2008.

Kalogerakis, K. S., Slanger, T. G., Kendall, E. A., Pedersen, T. R., Kosch, M. J., Gustavsson, B., and Rietveld, M. T.: Remote Oxygen Sensing by Ionospheric Excitation (ROSIE), *Ann. Geophys.*, **27**, 2183-2189, 2009.

Kosch, M. J., T. Pedersen, E. Mishin, M. Starks, E. Gerken-Kendall, D. Sentman, S. Oyama, and B. Watkins, Temporal evolution of pump beam self-focusing at the High-Frequency Active Auroral Research Program, *J. Geophys. Res.*, **112**, A08304, doi:10.1029/2007JA012264, 2007.

Kosch, M. J., M. T. Rietveld, T. Hagfors, and T. B. Leyser, High-latitude HF-induced airglow displaced equatorwards of the pump beam, *Geophys. Res. Lett.*, **27**(17), 2817–2820, 2000.

Kosch, M. J., B. Gustavsson, C. Heinselman, T. Pedersen, M.T. Rietveld, J. Spaleta, A. Wong, W. Wang, C. Mutiso, B. Bristow, J. Hughes, First incoherent scatter radar observations of ionospheric heating on the second electron gyro-harmonic, *Journal of Atmospheric and Solar-Terrestrial Physics*, **71**, 17-18, pp 1959-1966, ISSN 1364-6826, DOI: 10.1016/j.jastp.2009.08.007, 2009.

Kubota, M., T. Nagatsuma, and Y. Murayama, Evening co-rotating patches: A new type of aurora observed by high sensitivity all-sky cameras in Alaska, *Geophys. Res. Lett.*, **30**(12), 1612, doi:10.1029/2002GL016652, 2003.

Kuo, S.P., T. Pedersen, and T. Mills, Lateral Distribution of Atomic Oxygen Flux Produced by an Array of Three Fan-Shaped Plasma Torches, *IEEE Transactions on Plasma Science,* **36**, Issue 4, Page(s):1056 – 1057, 2008.

Leyser, T. B. L. Norin, M. McCarrick, T. R. Pedersen, and B. Gustavsson, Radio Pumping of Ionospheric Plasma with Orbital Angular Momentum, *Physical Review Letters*, **102**, Issue 6, id. 065004, 2009.

Lockwood, M., J. A. Davies, J. Moen, A. P. van Eyken, K. Oksavik, I. W. McCrea, and M. Lester, Motion of the dayside polar cap boundary during substorm cycles: II. Generation of poleward-moving events and polar cap patches by pulses in the magnetopause reconnection rate, *Annales Geophysicae*, **23**, Issue 11, pp.3513-3532, 2005a.

Lockwood, M., J. Moen, A. P. van Eyken, J. A. Davies, K. Oksavik, and I. W. McCrea, Motion of the dayside polar cap boundary during substorm cycles: I. Observations of pulses in the magnetopause reconnection rate, *Annales Geophysicae*, **23**, Issue 11, pp.3495-3511, 2005b.

Lorentzen, D. A., P. M. Kintner, J. Moen, F. Sigernes, K. Oksavik, Y. Ogawa, and J. Holmes, Pulsating dayside aurora in relation to ion upflow events during a northward interplanetary magnetic field (IMF) dominated by a strongly negative IMF BY, *Journal of Geophysical Research*, **112**, A03301, doi:10.1029/2006JA011757, 2007.

MacDougall, J., and P. T. Jayachandran, Polar patches: Auroral zone precipitation effects, *J. Geophys. Res.*, **112**, A05312, doi:10.1029/2006JA011930, 2007.

Moen, J., N. Gulbrandsen, D. A. Lorentzen, and H. C. Carlson, On the MLT distribution of F region polar cap patches at night, *Geophys. Res. Lett.*, **34**, L14113, doi:10.1029/2007GL029632, 2007.

Moen, J., H. C. Carlson, K. Oksavik, C. P. Nielsen, S. E. Pryse, H. R. Middleton, I. W. McCrea, and P. Gallop, EISCAT observations of plasma patches at sub-auroral cusp latitudes, *Annales Geophysicae*, **24**, Issue 9, pp.2363-2374, 2006.

Mutiso, C. K., J. M. Hughes, G. G. Sivjee, T. Pedersen, B. Gustavsson, and M. J. Kosch, Previously unreported optical emissions generated during ionospheric heating, *Geophys. Res. Lett.*, **35**, L14103, doi:10.1029/2008GL034563, 2008.

Pedersen, T. R., and H. C. Carlson, First observations of HF heater-produced airglow at the High Frequency Active Auroral Research Program facility: Thermal excitation and spatial structuring, *Radio Sci.*, **36**(5), 1013–1026., 2001.

Pedersen, T. R., M. McCarrick, E. Gerken, C. Selcher, D. Sentman, H. C. Carlson, and A. Gurevich, *Geophys. Res. Lett.*, **30,** 4, doi10:1029/2002GL016096, 2003

Pedersen, T. R., and E. A. Gerken, Creation of visible artificial optical emissions in the aurora by high-power radio waves, *Nature*, **433**(7025), 498–500, doi:10.1038/nature03243, 2005.

Pedersen, T., E. Mishin, and K. Oksavik, Observations of structured optical emissions and particle precipitation equatorward of the traditional auroral oval, *J. Geophys. Res.*, **112**, A10208, doi:10.1029/2007JA012299, 2007.

Pedersen, T., R. Esposito, E. Kendall, D. Sentman, M. Kosch, E. Mishin, and R. Marshall, Observations of artificial and natural optical emissions at the HAARP facility, *Ann. Geophys*., **26**, 1089-1099, 2008a.

Pedersen, T., R. Esposito, M. Starks, and M. McCarrick, Quantitative determination of HF radio-induced optical emission production efficiency at high latitudes, *J. Geophys. Res.*, **113**, A11316, doi:10.1029/2008JA013502, 2008b.

Pedersen, T., E. Mishin, and R. Esposito, New observations of HF-induced optical emissions from the ionospheric *E* region, *J. Geophys. Res.*, **114**, A06316, doi:10.1029/2008JA013596, 2009a.

Pedersen, T., B. Gustavsson, E. Mishin, E. MacKenzie, H. C. Carlson, M. Starks, and T. Mills, Optical ring formation and ionization production in high-power HF heating experiments at HAARP, *Geophys. Res. Lett.*, **36**, L18107, doi:10.1029/2009GL040047, 2009b.

Rietveld, M. T., M. J. Kosch, N. F. Blagoveshchenskaya, V. A. Kornienko, T. B. Leyser, and T. K. Yeoman, Ionospheric electron heating, optical emissions, and striations induced by powerful HF radio waves at high latitudes: Aspect angle dependence, *J. Geophys. Res.*, **108**(A4), 1141, doi:10.1029/2002JA009543, 2003.

Sobral, J. H. A., et al., Ionospheric zonal velocities at conjugate points over Brazil during the COPEX campaign: Experimental observations and theoretical validations, *J. Geophys. Res.*, 114, A04309, doi:10.1029/2008JA013896, 2009.

Valladares, C. E., T. Pedersen, and R. Sheehan, Polar Cap Patches Observed during the Magnetic Storm of November 2003: Observations and Modeling, *submitted* to *Journal of Geophysical Research*, 2008.

Yin, P., C.N. Mitchell, P. Spencer, I. McCrea, and T. Pedersen, A multi-diagnostic approach to understanding high-latitude plasma transport during the Halloween 2003 storm, *Annales Geophysicae*, **26**, Issue 9, 2008, pp.2739-2747, 2008.